HESS
Supporting Information for

Suspended sediment concentrations in Alpine rivers: from annual regimes to sub-daily extreme events

Amber van Hamel[1,2,3], Peter Molnar[4], Joren Janzing[1,2,3] and Manuela Irene Brunner[1,2,3]

[1]WSL Institute for Snow and Avalanche Research SLF, Davos Dorf, Switzerland
[2]Institute for Atmospheric and Climate Science, ETH Zurich, Zurich, Switzerland
[3]Climate Change, Extremes and Natural Hazards in Alpine Regions Research Center CERC, Davos Dorf, Switzerland
[4]Institute of Environmental Engineering, ETH Zurich, Zurich, Switzerland

Table S1. Root mean squared error (RMSE) and R-squared for the linear model, the non-linear model, and the non-linear model with log-transformed data used to predict SSC based on turbidity data. The results are shown for each of the eight Swiss stations.

	RMSE			R-squared		
	Linear	Non-linear	Non-linear-Log	Linear	Non-linear	Non-linear-Log
CH_2009	566.4	566.2	588.9	0.46	0.46	0.41
CH_2020	311.2	302.5	405.2	0.57	0.60	0.41
CH_2056	172.6	169.3	233.5	0.51	0.52	0.46
CH_2085	97.3	96.1	104.9	0.51	0.52	0.46
CH_2109	92.1	89.1	108.6	0.77	0.79	0.70
CH_2170	173.7	156.5	340.9	0.80	0.84	0.23
CH_2181	122.8	121.2	159.5	0.77	0.78	0.72
CH_2473	783.4	773.9	916.5	0.65	0.65	0.52

Table S2. The calibrated parameters a and b for the non-linear regression model for each of the eight Swiss stations.

	a	b
CH_2009	1.549	1.027
CH_2020	9.067	0.767
CH_2056	0.430	1.181
CH_2085	0.779	1.201
CH_2109	1.768	0.895
CH_2170	3.411	0.842
CH_2181	1.774	0.906
CH_2473	4.098	0.881

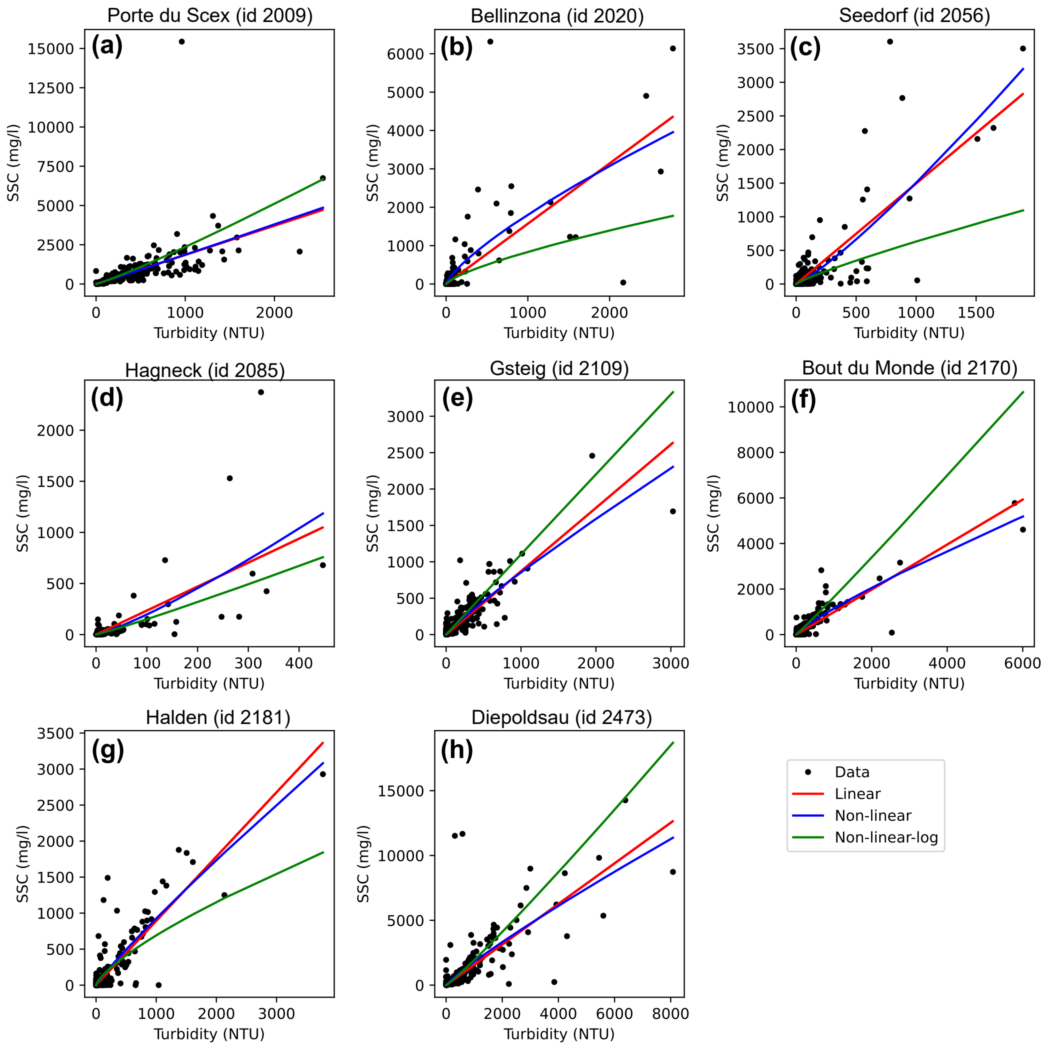

Figure S1. SSC bi-weekly samples plotted against the associated 10-minute turbidity measurements. The linear model (red), the non-linear model (blue), and the log-transformed non-linear model (after back transformation) (green) are shown for each of the eight Swiss stations.

Characteristics related to sediment transport			
Attribute	**Description**	**Unit**	**Data source**
slope_mean	Mean catchment slope	°C	QGIS and DEM / CamelsCH
Tmean_daily_mean	Mean daily air temperature	°C	CERRA
Tmean_daily_std	Standard deviation of mean daily air temperature	°C	CERRA
tp_daily_mean	Mean daily precipitation	mm d^{-1}	INCA and CPC
tp_daily_std	Standard deviation of mean daily precipitation	mm d^{-1}	INCA and CPC
tp_hourly_mean	Mean hourly precipitation	mm h^{-1}	INCA and CPC
tp_hourly_std	Standard deviation of mean hourly precipitation	mm h^{-1}	INCA and CPC
liqvsm_daily_mean	Mean daily liquid volumetric soil moisture	m^3 m^{-3}	CERRA-Land
liqvsm_daily_std	Standard deviation of mean daily liquid volumetric soil moisture	m^3 m^{-3}	CERRA-Land
icem_daily_std	Mean daily glacial melt	mm d^{-1}	PCR-GLOBWB 2.0
icem_daily_std	Standard deviation of mean daily glacial melt	mm d^{-1}	PCR-GLOBWB 2.0
snom_daily_mean	Mean daily snowmelt	mm d^{-1}	PCR-GLOBWB 2.0
snom_daily_std	Standard deviation of mean daily snowmelt	mm d^{-1}	PCR-GLOBWB 2.0
snocov_daily_mean	Mean daily snow cover	%	PCR-GLOBWB 2.0
doy_swe_zero	Day of the year on which the snow water equivalent reaches zero (or a minimum)	-	PCR-GLOBWB 2.0
p_frac_snow	Fraction of precipitation that falls as snow	-	LamaH-CE / CAMELS-CH
Qspecific_mean_d	Mean daily specific runoff	mm d^{-1}	Observations
high_q_freq	Frequency of high-flow days (≥ 9 times median daily flow)	d yr^{-1}	LamaH-CE / CAMELS-CH
high_prec_freq	Frequency of high-precipitation days (≥ 5 times mean daily precipitation)	d yr^{-1}	LamaH-CE / CAMELS-CH
runoff_ratio	Runoff ratio, computed as the ratio of mean daily runoff and mean daily precipitation	-	Calculated from Q observations and daily prepitation from INCA and CPC
stream_elas	Runoff-precipitation elasticity, i.e., the sensitivity of runoff to changes in precipitation at the annual timescale, using the mean daily runoff as reference	-	LamaH-CE / CAMELS-CH

Figure S2. Selected static catchment characteristics that are related to sediment transport processes.

Catchment characteristics related to sediment availability			
Attribute	**Description**	**Unit**	**Data source**
area	Catchment area	km^2	LamaH-CE / CAMELS-CH
elev_mean	Mean catchment elevation	m.a.s.l.	LamaH-CE / CAMELS-CH
elev_ran	Range in catchment elevation (maximum - minimum elevation)	m	LamaH-CE / CAMELS-CH
urban_fra	Fraction of urban land (CLC classes 111, 112, 121, 122, 123, 124)	-	LamaH-CE / CAMELS-CH via CORINE
forest_fra	Fraction of forest land (CLC classes 311, 312, 313)	-	See above
glac_fra	Fraction of glaciers (CLC class 335)	-	See above
geo_low_ero_fra	Fraction of low erodible geology classes (incl. acid plutonic, intermediate plutonic, and basic plutonic rocks, metamorphites, carbonate sedimentary rocks, acid volcanic rocks)	-	LamaH-CE / CAMELS-CH via GLiM, geology classes clustered via method by Moosdorf et al. 2018
geo_med_ero_fra	Fraction of median erodible geology classes (incl. siliciclastic sedimentary rocks, mixed sedimentary rocks, basic volcanic rocks, pyroclastics)	-	See above
geo_high_ero_fra	Fraction of high erodible geology classes (incl. unconsolidated sediments)	-	See above
sand_fra	Fraction of sand (of soil material < 2 mm)	-	LamaH-CE / CAMELS-CH via European Soil Database Derived data
Silt_clay_fra	Fraction of silt and clay (of soil material < 2 mm)	-	See above
grav_fra	Fraction of gravel (of overall soil)	-	See above
org_fra	Fraction of organic material (of overall soil)	-	See above
elon_ratio	Elongation ratio (Re) after Schumm (1956); ratio between the diameter D of a circle with an equivalent area as the area of the catchment, to the catchment length (Lc), $Re = 1/Lc \times \sqrt{(4 \times A/\pi)} = D/Lc$	-	LamaH-CE / QGIS and DEM
strm_dens	Stream density (DF); ratio of the total lengths of the streams (Lf) and the catchment area (A), $DF = \sum Lf / A$	$km\ km^{-2}$	See above
meand_indx	Meandering index (Mi); ratio of the horizontal stream length (Ls) to the catchment length (Lc), $Mi = Ls / Lc$	$km\ km^{-1}$	See above
Upstr_lake_prec	Percentage of catchment area that is located upstream of big lakes (lake area > $1 km^2$)	%	QGIS
Upstr_resv_perc	Percentage of catchment area located upstream of reservoirs	%	QGIS

Figure S3. Selected static catchment characteristics that are related to sediment availability.

Time-varying characteristics		
Description	**Unit**	**Data source**
Hourly precipitation	$mm\ d^{-1}$	INCA and CPC
Daily glacial melt	$mm\ d^{-1}$	PCR-GLOBWB 2.0
Daily snowmelt	$mm\ d^{-1}$	PCR-GLOBWB 2.0
Daily specific runoff	$mm\ d^{-1}$	Observations
Daily liquid volumetric soil moisture	$m^3\ m^{-3}$	CERRA-Land
Daily snow cover; percentage of catchment area that is snow-covered (with snow water equivalent > 0.1mm)	%	PCR-GLOBWB 2.0
Daily proxy for sediment availability; ratio between the annual cumulative sSSY and the long-term cumulative sSSY regime to see if more/less sediment than usual has been mobilized in the catchment during earlier events.	-	Calculated from SSC and discharge observations

Figure S4. Selected time-varying hydro-climatic and catchment-related characteristics.

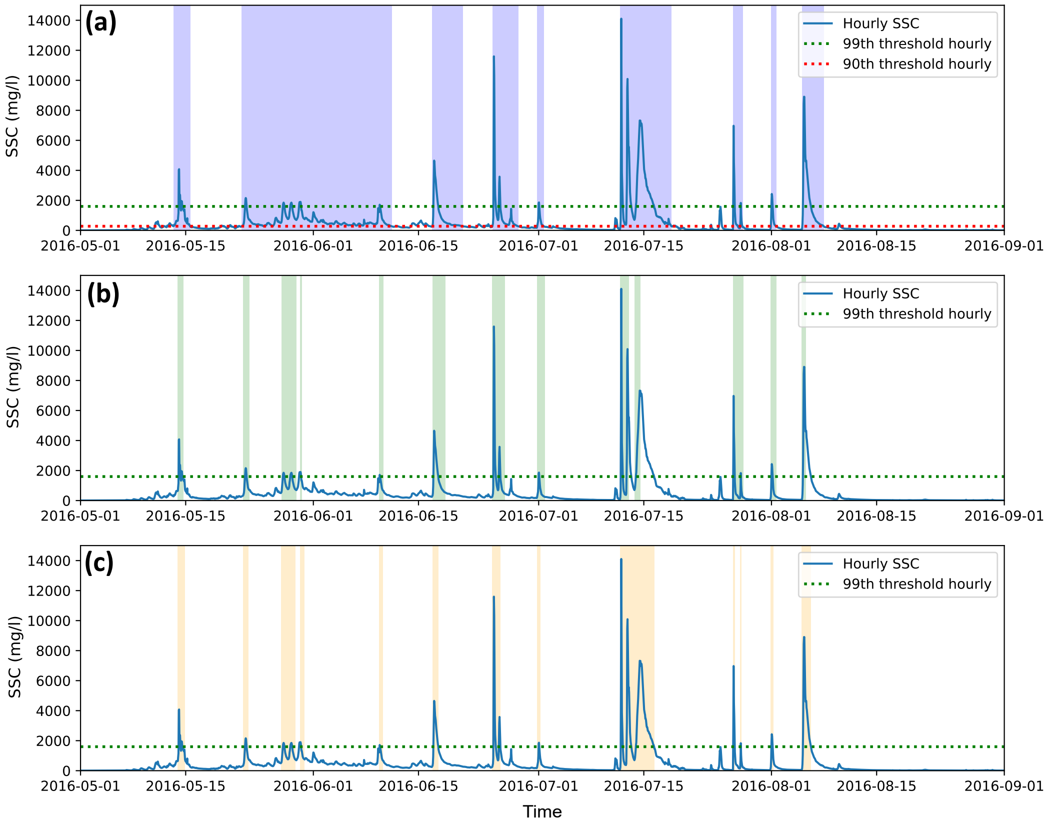

Figure S5. Comparison of three different methods to define the end of extreme SSC events. The peak value of all events exceeds a locally defined 99th percentile threshold and the start of the event is based on a rapid increase in the slope of SSC prior to the SSC peak. The end of the event is defined as (a) the first time step after peak SSC on which the SSC is below the 90th percentile threshold, (b) the first time step when the slope is less than Δ -10 mg l^{-1} h^{-1}, and (c) the first time step when the SSC is below $0.4 * peak\_SSC$ or the 99th threshold (lowest value is selected).

Table S3. Number of extreme SSC events and the percentage of the total number of events per event type. The results are shown for three methods that have a different definition for the start- and end of the events. Method 1: start/end when the SSC is above/below a fixed 90th percentile threshold. Method 2: start and end when the slope is more than Δ +20 / Δ -10 SSC/hour. Method 3: Start when the slope exceeds Δ +20 and the end when the SSC is below $0.4 * peak\_SSC$ or the 99th threshold (lowest value is selected).

	Number of events (-)			Percentage of total number (%)		
	Method 1	Method 2	Method 3	Method 1	Method 2	Method 3
Total events	2020	2423	2398	100.0	100.0	100.0
RainH	1353	1540	1547	67.0	63.6	64.5
RainL	400	504	494	19.8	20.8	20.6
Snow	79	124	110	3.9	5.1	4.6
RainL & Snow	70	86	82	3.5	3.5	3.4
RainH & Snow	50	57	56	2.5	2.4	2.3
Ice	35	54	54	1.7	2.2	2.3
RainL & Ice	15	25	23	0.7	1.0	1.0
RainH & Ice	12	20	22	0.6	0.8	0.9
Snow & Ice	6	13	10	0.3	0.5	0.4

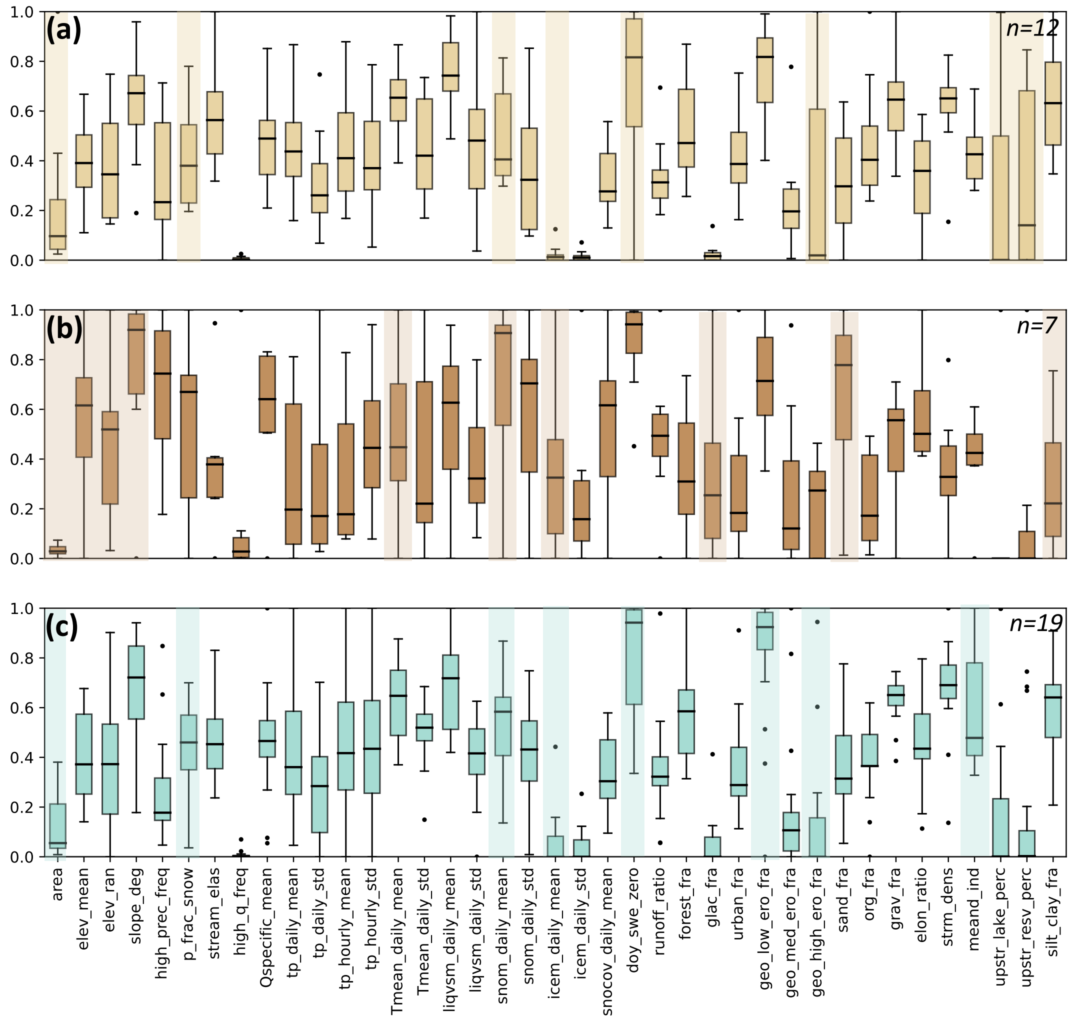

Figure S6. (a) Distribution of all static catchment characteristics for the catchments that belong to (a) Cluster 1, (b) Cluster 2, and (c) Cluster 3. To be able to compare the results within and among clusters, all catchment-related and hydro-meteorological attributes were normalized to the range 0-1 (z-score).

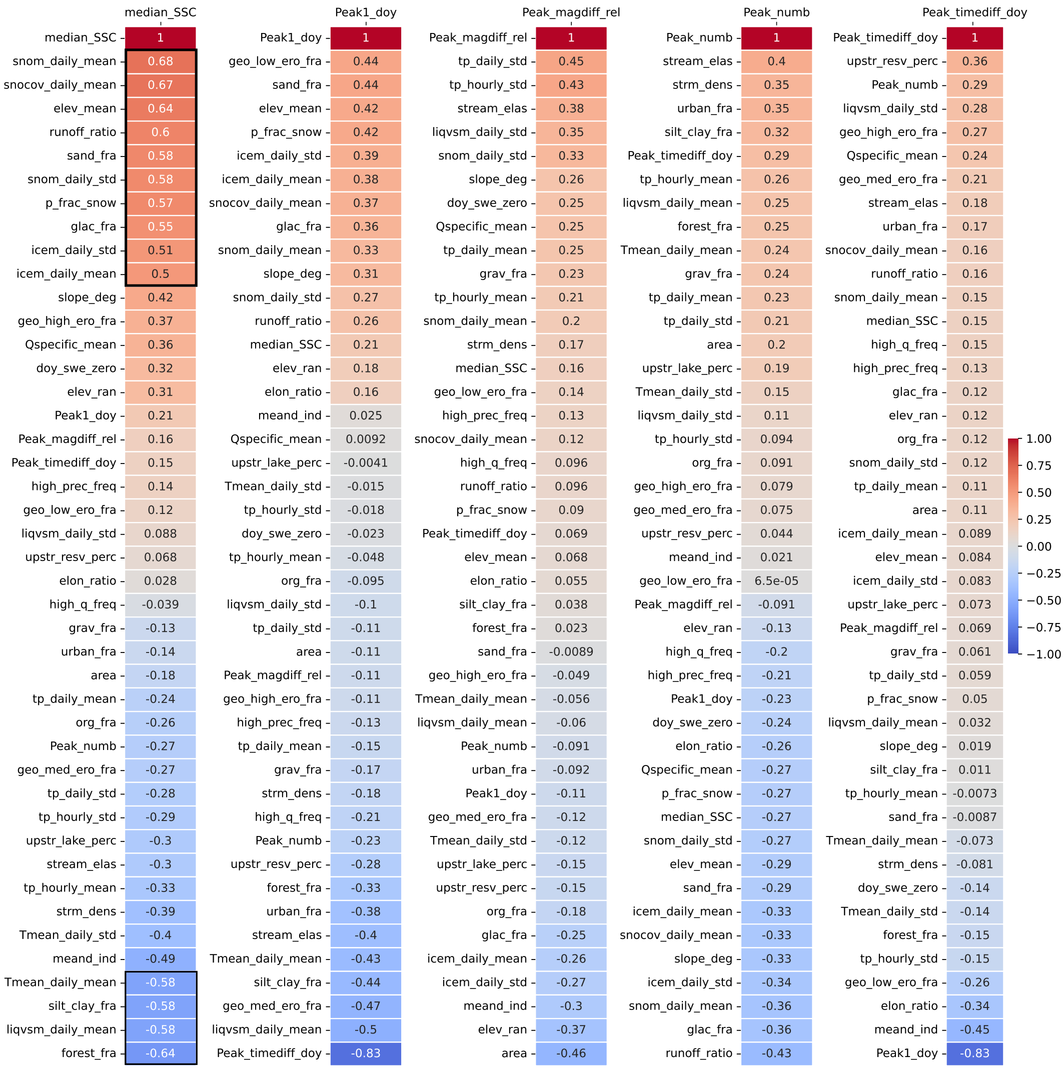

Figure S7. Pearson correlations of the static characteristics with the five MST-indicators that have been used for the clustering of the annual SSC cycles. The black boxes highlight the static characteristics that show a moderate correlation (correlation coefficient >0.5) with the magnitude of the SSC regime (*median_ SSC*).

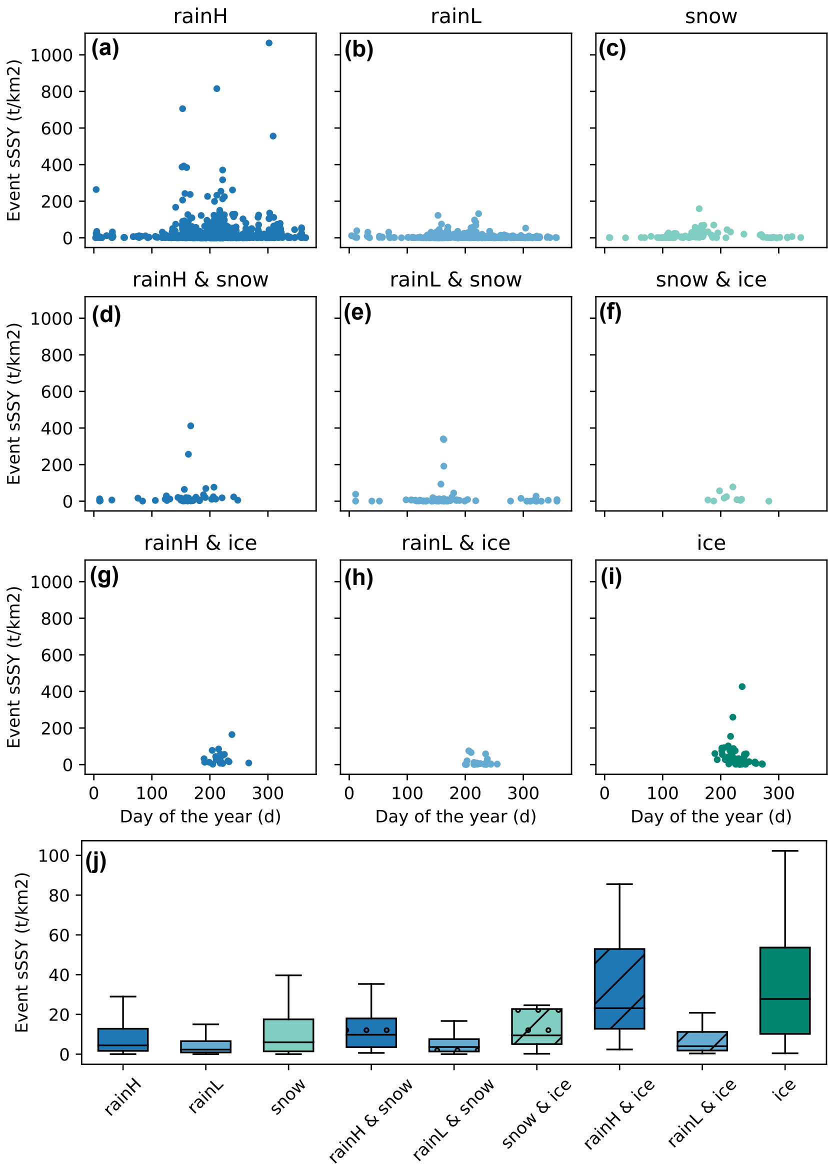

Figure S8. Area-specific suspended sediment yield (sSSY) is grouped by event type. Panels (a-i) illustrate the variation of sSSY over time with the outliers. Panel(j) illustrates the distribution of sSSY for each even type (without outliers), with the median value represented by a horizontal black line.

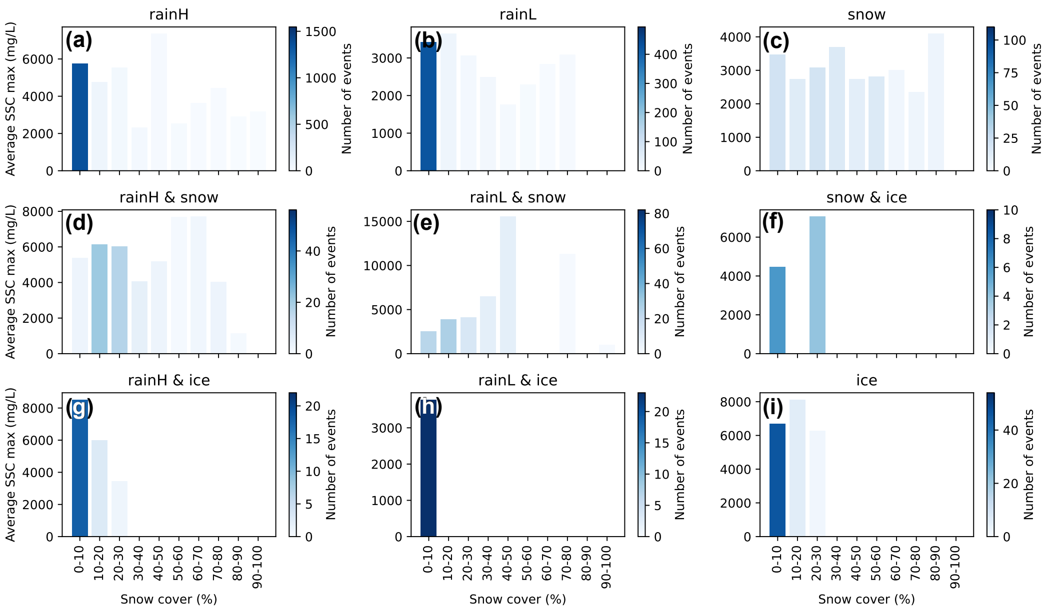

Figure S9. Snow cover prior to extreme SSC events can vary from 0-100%. Per event type and for each of the 10 intervals, the bars show the average SSC maximum for all events that belong to one of the intervals. The color saturation is an indication for the number of events per event type that belongs to each of the intervals. Dark blue means that most events of that event type belong to that interval.

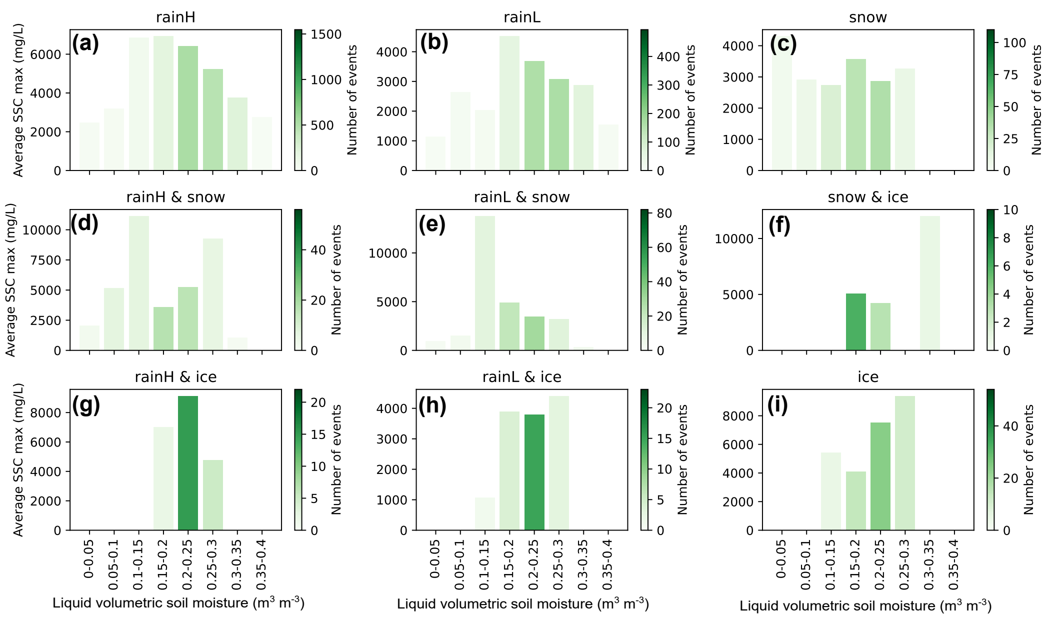

Figure S10. Liquid volumetric soil moisture generally varies from 0-0.4 m^3/m^3. Per event type and for each of the 8 intervals, the bars show the average SSC maximum for all events that belong to one of the intervals. The color saturation is an indication for the number of events per event type that belongs to each of the intervals. Dark green means that most events of that event type belong to that interval.

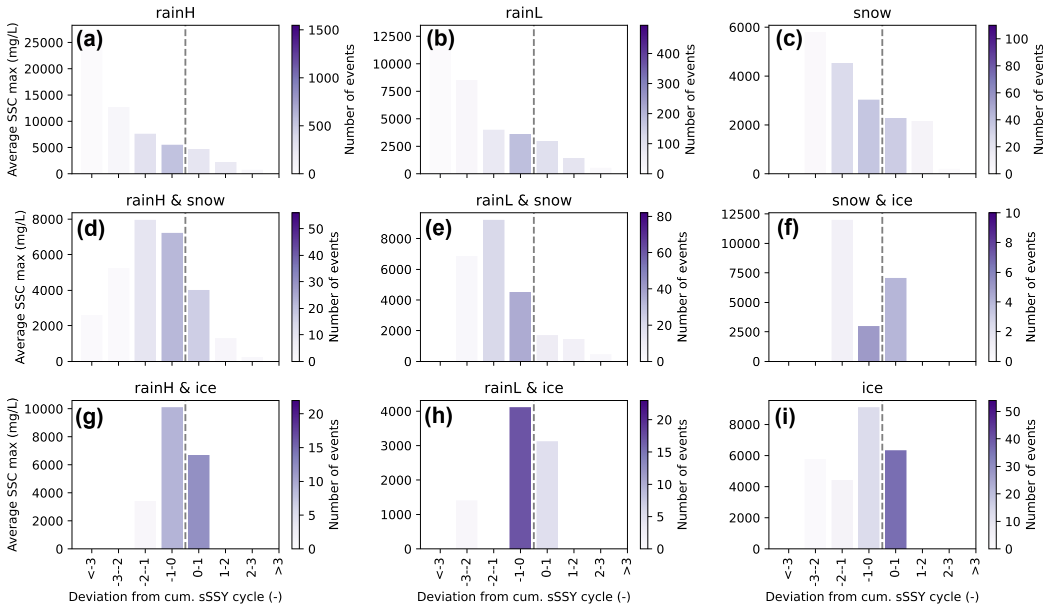

Figure S11. Prior to the extreme SSC event, the deviation of the daily cumulative sSSY from the annual mean cumulative sSSY cycle can be positive or negative. Positive values indicate that prior to the event, more sediment has been transported by the river than usual. Negative values indicate that less sediment than usual has been transported. Per event type and for each of the 8 intervals, the bars show the average SSC maximum for all events that belong to one of the intervals. The color saturation is an indication for the number of events per event type that belongs to each of the intervals. Dark purple means that most events of that event type belong to that interval.